PATENT ABSTRACTS OF JAPAN

(11)Publication number : 08-148113
(43)Date of publication of application : 07.06.1996

(51)Int.CI. H01J 43/12
H01L 31/107

(21)Application number : 06-290070
(22)Date of filing : 24.11.1994

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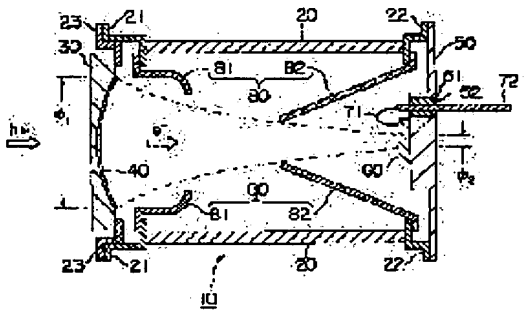
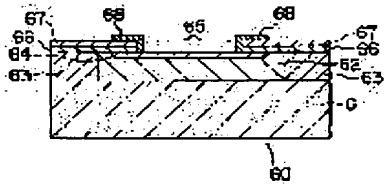
(54) PHOTOMULTIPLIER

(57)Abstract:
PURPOSE: To largely improve energy resolution by disposing a carrier multiplication layer obtained by epitaxial growth and a breakdown voltage control layer of dopant concentration higher than the former on a semiconductor element opposite to a photocathode.
CONSTITUTION: A photocathode 40 for producing photoelectrons due to photons, a semiconductor element 66 for multiplying photoelectrons, opposite to it, and electron lenses 80 converging photoelectrons are disposed in a high-vacuum vessel comprising an enclosure 20, a light incident window 30 and a stem 50. In a photomultiplier tube 10, as above, a carrier multiplication layer 62 with dopant obtained by epitaxial growth being uniformly distributed is disposed on a semiconductor substrate 61 of a semiconductor element 60. A breakdown voltage control layer 64 of dopant concentration higher than the former is disposed on the layer. A photoelectron receiving portions 65 is partly exposed by means of an insulating layer 67 and an ohmic electrode layer 68. Accordingly, uniformity in avalanche multiplication gain for photoelectrons is attached and energy resolution is largely raised, so that high sensitive and quantitative measurement of faint light becomes possible.





LEGAL STATUS

[Date of request for examination] 30.07.2001
[Date of sending the examiner's decision of rejection] 26.11.2003
[Kind of final disposal of application other than the examiner's decision of rejection or application converted registration]
[Date of final disposal for application]
[Patent number]
[Date of registration]

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CLAIMS

[Claim(s)]
[Claim 1] The photoelectric cathode which emits into a vacuum the envelope which holds the interior to a high vacuum, and the photoelectron which it was formed in the vacuum side of the entrance window of this envelope, and was excited by incident light, It counters with this photoelectric cathode, is installed in the interior of said envelope, and has the semiconductor device which detects said photoelectron emitted from the photoelectric cathode concerned. Said semiconductor device The semi-conductor substrate of the 1st conductivity type, and the carrier multiplication layer of the 2nd conductivity type formed by growing epitaxially on this semi-conductor substrate, By being formed on the breakdown voltage control layer of the 2nd conductivity type which is formed on this carrier multiplication layer and has larger dopant concentration than the dopant concentration of the carrier multiplication layer concerned, and this breakdown voltage control layer The photomultiplier tube characterized by consisting of ohmic electrode layers in which the front face of the breakdown voltage control layer concerned is partially exposed as the acceptance section of said photoelectron.
[Claim 2] It is the photomultiplier tube according to claim 1 which is installed between said photoelectric cathode and said semiconductor devices, is further equipped with the electron lens which converges said photoelectron emitted from the photoelectric cathode concerned, and is led to said acceptance section of the semiconductor device concerned, and is characterized by the aperture of said acceptance section being 10mm or less.
[Claim 3] The circumference of the front face exposed as said acceptance section of said breakdown voltage control layer is the photomultiplier tube according to claim 1 or 2 characterized by being covered with the insulating layer which consists of a nitride.

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DETAILED DESCRIPTION

[Detailed Description of the Invention]
[0001]
[Industrial Application] the fluorescence which this invention is the photomultiplier tube which detects a feeble light which cannot be sensed with a naked eye by the sensibility which reaches a quantum limitation, and is generated more from the living body minute amount matter in a detail -- a single photoelectron -- it is related with the photomultiplier tube quantitatively measured by counting.
[0002]
[Description of the Prior Art] There are some which built in the avalanche photo-diode (APD; Avalanche Photo Diode) as a semiconductor device which amplifies and detects the photoelectron which there are various kinds of things in the conventional photomultiplier tube, for example, was emitted from photoelectric cathode. Such APD, especially APD of a bulk mold consist of various conductivity-type fields formed in the semi-conductor substrate by the diffusion method, ion-implantation, etc.
[0003] In addition, the advanced technology about such the photomultiplier tube is indicated by "United States Patent, No.5146296, Sep., 1992", "LASER FOCUS WORLD, pp.125-132, Nov., 1993", etc. at the detail.
[0004]
[Problem(s) to be Solved by the Invention] However, in the above-mentioned conventional photo-multiplier, the avalanche multiplication gain over a photoelectron is greatly dependent on the incidence location of the photoelectron in APD, and differs, and good uniformity cannot be obtained. Therefore, when two or more photoelectrons carry out incidence to the location where the acceptance sections of APD differ, there is a problem [energy resolution] of being inadequate, practical.
[0005] The electron lens which converges a photoelectron and is made to irradiate the acceptance section of APD as one of the approaches of solving this problem is installed. However, it is theoretically impossible to complete the photoelectron emitted from photoelectric cathode with this electron lens as one on the acceptance section of APD. Therefore, since incidence of each photoelectron is carried out to the location where the acceptance sections of APD differ, it has fully come to cancel the heterogeneity of the avalanche multiplication gain over a photoelectron too.
[0006] In addition, installation of such an electron lens is indicated by JP,5-54849,A at the detail, for example.
[0007] Moreover, building in a photodiode (PD; Photo Diode) is performed as a semiconductor device which amplifies and detects the photoelectron emitted from photoelectric cathode as one of the approaches of solving the above-mentioned problem. This PD is constituted as a location sensing element which arranged plurality superficially. However, since such PD does not have avalanche multiplication gain, total gain is comparatively small. Therefore, there is a problem that a single photoelectron is easily undetectable.
[0008] In addition, the advanced technology about such the photomultiplier tube "Nucl.Instr.and Meth., vol.A310 and pp.261-266, 1991""Nucl.Instr.and Meth., vol.A315, and pp.375-384, 1992""Nucl.Instr.and Meth. and vol. -- A330, pp.93-99, and 1993" -- it is indicated by "HYBRID PHOTOMULTIPLIER TUBES, Delft Electronische Producten", etc. at the detail.
[0009] Then, this invention is made in view of the above trouble, and aims at offering the photomultiplier tube which raises energy resolution sharply by attaining the uniformity of the avalanche multiplication gain over a photoelectron in the electron tube which contained the semiconductor device which has an avalanche multiplication layer.
[0010]
[Means for Solving the Problem] The photomultiplier tube of this invention was formed in the vacuum side

of the entrance window of the envelope which holds the interior to a high vacuum in order to attain the above-mentioned purpose, and this envelope, it countered with the photoelectric cathode which emits into a vacuum the photoelectron excited by incident light, and this photoelectric cathode, was installed in the interior of an envelope, and is equipped with the semiconductor device which detects the photoelectron emitted from the photoelectric cathode concerned.

[0011] The carrier multiplication layer of the 2nd conductivity type formed by a semiconductor device growing epitaxially here on the semi-conductor substrate of the 1st conductivity type, and this semi-conductor substrate, By being formed on the breakdown voltage control layer of the 2nd conductivity type which is formed on this carrier multiplication layer and has larger dopant concentration than the dopant concentration of the carrier multiplication layer concerned, and this breakdown voltage control layer It is characterized by consisting of ohmic electrode layers in which the front face of the breakdown voltage control layer concerned is partially exposed as the acceptance section of a photoelectron.

[0012] In addition, it is installed between photoelectric cathode and a semiconductor device, and has further the electron lens which converges the photoelectron emitted from the photoelectric cathode concerned, and is led to the acceptance section of the semiconductor device concerned, and the aperture of the acceptance section is good also considering being 10mm or less as a description.

[0013] Moreover, the circumference of the front face exposed as the acceptance section of a breakdown voltage control layer is good also considering being covered with the insulating layer which consists of a nitride as a description.

[0014]

[Function] In the photomultiplier tube of this invention, if a predetermined electrical potential difference is impressed from an external voltage source, inside an envelope, the electric field which go to photoelectric cathode from a semiconductor device will occur. Moreover, since a reverse bias electrical potential difference is impressed to the interior of a semiconductor device, the depletion layer (avalanche multiplication field) prolonged toward the breakdown voltage control layer from the plane of composition of a semi-conductor substrate and a carrier multiplication layer generates.

[0015] Here, if an external feeble light carries out incidence to the entrance window of an envelope as a photon, this photon will penetrate the interior of an entrance window, and will be absorbed by photoelectric cathode. Therefore, the electron located in the valence band of photoelectric cathode excites to a conduction band, and is emitted by negative electron affinity operation into a vacuum as a photoelectron. Thus, the photoelectron emitted from photoelectric cathode counters the electric field which go to photoelectric cathode from a semiconductor device, and carries out incidence to the acceptance section of a semiconductor device.

[0016] Whenever the photoelectron which carried out incidence to the acceptance section of a semiconductor device loses energy predetermined in the interior of a carrier multiplication layer, it generates the electronic-electron hole pair of a pair. Therefore, thousands of sets of electronic-electron hole pairs occur as a secondary carrier by the incidence of a single photoelectron. Since the gain over the photoelectron in this process, i.e., electron irradiation gain, is determined by the incidence energy of a photoelectron, it has good uniformity to the incidence location of the photoelectron in the acceptance section of a semiconductor device.

[0017] The drift of the secondary carrier which carried out multiplication immediately after this electron irradiation is countered and carried out to the electric field which go to a semi-conductor substrate or a breakdown voltage control layer from a carrier multiplication layer. One carrier of this secondary carrier arrives at the avalanche multiplication field generated inside the carrier multiplication layer. Thus, the drift was carried out, and since it repeats, the process, i.e., avalanche multiplication, in which a carrier collides with the molecule which constitutes a carrier multiplication layer, and ionization is caused, a dozens times as many electronic-electron hole pair as this is generated further. While carried out avalanche multiplication, the drift of the carrier is countered and carried out to this electric field that go to a semi-conductor substrate or a breakdown voltage control layer from a carrier multiplication layer, and it reaches a semi-conductor substrate or a breakdown voltage control layer.

[0018] Here, the dopant distribution is controlled very much by homogeneity by growing epitaxially and forming a carrier multiplication layer on the semi-conductor substrate which has a different conductivity type from this. Therefore, the gain over the photoelectron in this process, i.e., avalanche multiplication gain, is reducing the dependence over the generation-of-carriers location in a carrier multiplication layer, and it has good uniformity.

[0019] The reverse current corresponding to the amount of multiplication of such a carrier is outputted to an

external arithmetic unit from an ohmic electrode layer. Therefore, based on the drive of an external arithmetic unit, the number of the photon which carried out incidence to the photomultiplier tube is detected according to an individual one by one. therefore, the sensibility which reaches a quantum limitation in a feeble light which cannot be sensed with a naked eye -- a single photoelectron -- it is quantitatively measurable with counting.

[0020]

[Example] Hereafter, the configuration and operation of an example concerning the photomultiplier tube of this invention are explained to a detail with reference to drawing 1 thru/or drawing 5 . In addition, in explanation of a drawing, the same sign is given to the same element, and the overlapping explanation is omitted. Moreover, the dimension ratio of a drawing is not necessarily in agreement with the thing of explanation.

[0021] As shown in 1st example drawing 1 , the photomultiplier tube 10 of this example carries out the closure of the both ends of the bell shape envelope 20 airtightly by the entrance window 30 and the stem 50, respectively, holds the interior to the high vacuum of pressure 10-8Torr extent, and is constituted. As an electron lens 80, two focal electrodes 81 and 82 approach photoelectric cathode 30 and a stem 50, and are installed in the interior of this photomultiplier tube 10, respectively, and the semiconductor device 60 is installed on the stem 50.

[0022] An envelope 20 is a bell shape glass by-pass. The bell shape attachment material 21 and 22 bent by two steps is installed in the both ends of this envelope 20, respectively. In addition, these attachment material 21 and 22 is formed with the covar metal, respectively.

[0023] An entrance window 30 is a disc-like glass face-plate, and has the flat surface and the concave surface, respectively as each front face by the side of atmospheric air and a vacuum. The bell shape attachment material 23 bent by two steps is installed in the vacuum side periphery section of this entrance window 30. The envelope 20 and the entrance window 30 are constituted by one by welding partially each edge of two attachment material 21 and 23. In addition, the glass ingredient of an entrance window 30 has permeability to the wavelength of the light made into the measuring object.

[0024] A stem 50 is a disc-like metal face-plate, and has heights as an installation field of a semiconductor device 60 in the vacuum side. The envelope 20 and the stem 50 are constituted by one by welding partially the vacuum side periphery section of this stem 50, and the edge of the attachment material 22. Moreover, the through hole 51 which inserts in the terminal rod 72 which a semiconductor device 60 mentions later is formed near the center section of the stem 50. In addition, this stem 50 is formed with the covar metal.

[0025] The thin film-like photoelectric cathode 40 is vapor-deposited and formed in the vacuum side front face of an entrance window 30. The predetermined electrical potential difference is impressed through the attachment material 23 from the external voltage source (not shown), for example, this photoelectric cathode 40 is [about / potential]. -It is held at 15kV. In addition, photoelectric cathode 40 is formed with alkali metal, for example, K, Na, Cs, Sb, etc. Moreover, in photoelectric cathode 40, incident light hnu is received, photo electric conversion is carried out with predetermined quantum efficiency, and it is Photoelectron e. - Aperture phi 1 to generate It is about 16mm.

[0026] The focal electrode 81 of the shape of a bowl which one step was bent and was penetrated is partially joined to the edge of the attachment material 21 by welding. This focal electrode 81 is installed with the posture countered and converged on a stem 50. The same electrical potential difference as the applied voltage of photoelectric cathode 40 is impressed through the attachment material 21 from an external voltage source (not shown), for example, the focal electrode 81 is [about / potential]. -It is held at 15kV. In addition, the focal electrode 81 is formed from stainless steel.

[0027] The focal electrode 82 of the shape of a hollow truncated cone which one step was bent and was penetrated is partially joined to the edge of the attachment material 22 by welding. This focal electrode 82 is installed with the posture which counters a stem 50 and is opened. the focal electrode 82 impresses a predetermined electrical potential difference through the attachment material 22 from an external voltage source (not shown) -- having -- for example, the potential 0 [about] -- it is held V. In addition, the focal electrode 82 is formed from stainless steel.

[0028] On the vacuum side heights of a stem 50, the acceptance section 65 which a semiconductor device 60 mentions later is made to counter photoelectric cathode 50, and it is installed. The electrode layer 66 which this semiconductor device 60 mentions later, and the metal terminal rod 72 which inserted in the through hole 51 of a stem 50 airtightly are electrically connected by carrying out bonding of the edge of the metal wire 71, respectively. the front-face side of a semiconductor device 60 impresses a predetermined electrical potential difference through the terminal rod 72 and a wire 71 from an external voltage source (not shown) -

- having -- about [for example, / potential] -- it is held -145V. moreover, the rear-face side of a semiconductor device 60 impresses the same electrical potential difference as the applied voltage of an electron lens 81 through a stem 50 from an external voltage source (not shown) -- having -- for example, the potential 0 [about] -- it is held V. Thereby, the reverse bias electrical potential difference is impressed to the semiconductor device 60 as a whole.

[0029] In addition, the terminal rod 72 is connected to the external arithmetic unit (not shown) which processes the detecting signal outputted from the semiconductor device 60. Moreover, between a through hole 51 and the terminal rod 72, the cylinder-like insulating material 52 closes airtightly, and is installed in it. Furthermore, it sets to a semiconductor device 60 and is Photoelectron e. - The aperture phi 2 which is received and is effectively amplified with a predetermined multiplication factor is about 3mm.

[0030] As shown in drawing 2 , the square pole-like semiconductor device 60 is constituted as APD. This semiconductor device 60 is the photoelectron e which was emitted from photoelectric cathode 30 and it converged with the electron lens 80. - It is the semiconductor detector amplified and detected in the avalanche multiplication field which the acceptance section 65 mentioned later irradiates and is mentioned later.

[0031] On the center section of the plate-like semi-conductor substrate 61, the disc-like carrier multiplication layer 62 is formed. On the periphery of this semi-conductor substrate 61, the circular ring-like guard ring layer 63 has the same thickness as the carrier multiplication layer 62, and is formed. The disc-like breakdown voltage control layer 64 is formed in the surface central field of the carrier multiplication layer 62.

[0032] The semi-conductor substrate 61 is the 1st conductivity type, i.e., n+. It is the high concentration single crystal wafer formed by Si of a mold. This semi-conductor substrate 61 has about 500 micrometers of thickness, and P is doped by concentration abbreviation 1019cm-3 as an n mold dopant, and it has specific resistance about 0.01 ohm-cm.

[0033] The carrier multiplication layer 62 is a low concentration semi-conductor layer formed by growing epitaxially on the semi-conductor substrate 61 in Si of the 2nd conductivity type, i.e., p mold. This carrier multiplication layer 62 has about 10 micrometers of thickness, and B is doped by concentration abbreviation 1014-1016cm-3 as a p mold dopant, and it has specific resistance about one to 100 ohm-cm. The dopant concentration of the carrier multiplication layer 62 is a value to which the depletion layer which spreads from a plane of composition with the semi-conductor substrate 61 reaches the breakdown voltage control layer 64, when the electrical potential difference close to breakdown voltage is impressed.

[0034] In addition, it is suitable for the thickness d to which epitaxial growth of the good crystallinity is held and carried out in this carrier multiplication layer 62 to set up so that it may be contained in the range of about 5 micrometers - about 50 micrometers. Since the heterogeneity of the dopant concentration of the direction of thickness becomes remarkable when larger than about 50 micrometers, Thickness d is Photoelectron e. - The uniformity of the receiving avalanche multiplication gain will be degraded depending on a generation-of-carriers location. On the other hand, since the depletion layer in which Thickness d extends and spreads from the semi-conductor substrate 61 when smaller than about 5 micrometers becomes thin, it is Photoelectron e. - The receiving electron irradiation gain will be reduced.

[0035] Here, the reason for having set Thickness d as about 10 micrometers is the photoelectron e irradiated by acceleration energy abbreviation 15keV. - It is Photoelectron e to about 3 micrometers of maximum ranges, and about 3 micrometers of thickness of the avalanche multiplication field mentioned later. - It is because some allowances were taken into consideration, respectively in order to press down the receiving fluctuation of electron irradiation gain to minimum.

[0036] The guard ring layer 63 is a high concentration semi-conductor layer formed by carrying out thermal diffusion of the n mold dopant to the periphery of the carrier multiplication layer 62 as a dopant of the 1st conductivity type. This guard ring layer 63 has about 10 micrometers of the same thickness as the thickness of the carrier multiplication layer 62, and P is doped as an n mold dopant by the concentration abbreviation 1019cm-3 [same] as the concentration of the semi-conductor substrate 61.

[0037] The breakdown voltage control layer 64 is a high concentration semi-conductor layer formed by carrying out thermal diffusion of the p mold dopant to the surface central field of the carrier multiplication layer 62 as a dopant of the 2nd conductivity type. This breakdown voltage control layer 64 has about 1 micrometer of thickness, and B is doped as a p mold dopant by the concentration abbreviation 1019cm-3 [same] as the concentration of the semi-conductor substrate 61. The acceptance section 65 of a circle configuration counters photoelectric cathode 40, and is exposed to the surface center section of this breakdown voltage control layer 64.

[0038] In addition, it sets in this acceptance section 65, and is Photoelectron e. - Aperture phi 2 which is received and is amplified with a predetermined multiplication factor It is suitable to set up so that it may be contained in the range of about 10mm or less. It is aperture phi 2. Since the heterogeneity of the dopant concentration of the direction of a front face becomes remarkable when larger than about 10mm, it is Photoelectron e. - The uniformity of the receiving avalanche multiplication gain will be degraded depending on a generation-of-carriers location. Moreover, since the capacity of an avalanche multiplication field becomes large, a working speed will decrease.
[0039] On most on the surface periphery section of the breakdown voltage control layer 64 located in the periphery of the acceptance section 65, and the whole front face of the guard ring layer 63, two kinds of insulating layers 66 and 67 carry out a laminating one by one, and are formed. An insulating layer 66 is the insulating thin film formed with the oxide of Si. The thickness of this insulating layer 66 is about 200nm. An insulating layer 67 is the insulating thin film formed with the nitride of Si. The thickness of this insulating layer 67 is about 50nm.
[0040] In addition, in case the guard ring layer 63 and the breakdown voltage control layer 64 are formed, in order to hold the crystallinity of the carrier multiplication layer 62 good, an insulating layer 66 oxidizes the surface field of the carrier multiplication layer 62 beforehand, and is formed. Moreover, in case photoelectric cathode 40 is formed, in order not to degrade the semi-conductor property of the carrier multiplication layer 62, the guard ring layer 63, and the breakdown voltage control layer 64, an insulating layer 67 is made to deposit on an insulating layer 66, and is formed.
[0041] The circular ring-like ohmic electrode layer 68 is formed on the insulating layer 67, and it is in contact with the surface periphery section of the breakdown voltage control layer 64 in accordance with the side attachment wall of insulating layers 66 and 67. This ohmic electrode layer 68 is the metal thin film formed with aluminum, and has good ohmic contact nature to the breakdown voltage control layer 64.
[0042] In addition, a predetermined electrical potential difference is impressed to the ohmic electrode layer 68 through the terminal rod 72 from an external voltage source (not shown) by the bonding of a wire 71, for example, it is held at the negative potential of -145V. Moreover, a predetermined electrical potential difference is impressed to the semi-conductor substrate 61 from an external voltage source (not shown) by installation on a stem 50, for example, it is held at the grand (GND) potential of 0V. Thereby, it is n+. The semi-conductor substrate 61 and p+ of a mold A depletion layer is generated as an avalanche multiplication field by between [62] the breakdown voltage control layers 64 of a mold (i.e., a carrier multiplication layer).
[0043] photoelectron e- which carried out incidence to the acceptance section 65 here electron irradiation gain until it arrives at an avalanche multiplication field -- about 4x103 it is . Avalanche multiplication gain until these carriers pass through an avalanche multiplication field and reach the semi-conductor substrate 61 is about 30. Thereby, a semiconductor device 60 is Photoelectron e as a whole. - The gain of the secondary electron to receive is 105. Extent is reached.
[0044] In addition, APD of the super-abrupt junction mold approximated to APD of such a step junction mold is indicated by JP,50-54290,A at the detail, for example.
[0045] Next, the production process of the semiconductor device 60 in this example is explained.
[0046] the usual CVD (Chemical Vapor Deposition) as the 1st step -- law -- being based -- n+ On the whole surface of the semi-conductor substrate 61 which consists of a mold Si, epitaxial growth of the p mold Si is carried out, and the carrier multiplication layer 62 of p mold is formed. Next, based on the usual oxidizing [thermally] method, the insulating layer 66 which the surface field of the carrier multiplication layer 62 is oxidized, and consists of an oxide of Si is formed. Then, the carrier multiplication layer 62 located in the method of a circumference subordinate of an insulating layer 66 is made to diffuse P alternatively as an n mold dopant based on the usual thermal diffusion method, and it is n+. The guard ring layer 63 of a mold is formed. Furthermore, the carrier multiplication layer 62 located in the method of a central subordinate of an insulating layer 66 is made to diffuse B alternatively as a p mold dopant based on the usual thermal diffusion method, and it is p+. The breakdown voltage control layer 64 of a mold is formed.
[0047] As the 2nd step, based on the usual CVD method, the nitride of Si is made to deposit and an insulating layer 67 is formed on the whole surface of an insulating layer 66. Next, based on the usual photolithography technique, a circular ring-like mask layer is formed on the periphery of an insulating layer 67. Then, based on the usual dry etching method, the center section of the insulating layers 66 and 67 is removed, the front face of the breakdown voltage control layer 64 is exposed, and the acceptance section 65 is formed. And based on the usual vacuum deposition method, on the acceptance section 65 and an insulating layer 67, aluminum is made to deposit and the ohmic electrode layer 68 is formed. Then, based on

the usual photolithography technique, a circular ring-like mask layer is formed on the surface field of the ohmic electrode layer 68 from the inside section of an insulating layer 67 to the periphery of the breakdown voltage control layer 64. Then, after removing the ohmic electrode layer 68 from on the center section of the breakdown voltage control layer 64 the periphery top of an insulating layer 67 based on the usual wet etching method, a mask layer is removed from on this fabricated ohmic electrode layer 68.
[0048] Next, actuation of this example is explained.
[0049] First, if a predetermined electrical potential difference is impressed from an external voltage source, while predetermined potential will generate to photoelectric cathode 40 and an electron lens 80, high potential generates by the electron lens 81 and the stem 50. Thereby, inside a vacuum housing 20, the electric field which pass each opening of electron lenses 80 and 81 from a semiconductor device 60, and go to photoelectric cathode 40 occur.
[0050] Moreover, while predetermined potential generates in the ohmic electrode layer 68, high potential generates with the semi-conductor substrate 61. Thereby, since the reverse bias electrical potential difference is impressed to the interior of a semiconductor device 60, the depletion layer prolonged toward the breakdown voltage control layer 64 from the plane of composition of the semi-conductor substrate 61 and the carrier multiplication layer 62 generates as an avalanche multiplication field.
[0051] Here, if an external feeble light, for example, the fluorescence generated from the living body minute amount matter, carries out incidence to the light sensing portion of an entrance window 30 as photon hnu, this photon hnu will penetrate the interior of an entrance window 30, and will be absorbed by photoelectric cathode 40. Therefore, the electron located in the valence band of photoelectric cathode 40 excites to a conduction band, and it is Photoelectron e by negative electron affinity operation. - It carries out and is emitted into a vacuum. Thus, photoelectron e emitted from photoelectric cathode 40 - It moves to the electric field wide opened toward photoelectric cathode 40 through the electron lens 80 from the stem 50 face to face, and incidence is carried out to the acceptance section 65 of a semiconductor device 60.
[0052] In addition, photoelectron e emitted from photoelectric cathode 40 with the electron lens 80 - It is the aperture phi 2 of the acceptance section 65 to make it converge on one on the acceptance section 65, although it is theoretically impossible. It is possible to make it converge on extent. Therefore, each photoelectron e - Incidence will be carried out to the location where the acceptance sections 65 differ.
[0053] Photoelectron e which carried out incidence to the acceptance section 65 of a semiconductor device 60 - Whenever it loses energy about 3.6eV inside the carrier multiplication layer 62, the electronic-electron hole pair of a pair is generated. Therefore, single photoelectron e - By incidence, thousands of sets of electronic-electron hole pairs occur as a secondary carrier. Thus, the drift of the secondary carrier which carried out multiplication is countered and carried out to the electric field which go to the breakdown voltage control layer 64 from the semi-conductor substrate 61. In this, an electron arrives at the avalanche multiplication field generated inside the carrier multiplication layer 62. At this time, it is Photoelectron e. - The receiving electron irradiation gain is about 4x103. It reaches.
[0054] The electron which carried out the drift to the avalanche multiplication field repeats the avalanche multiplication process in which collide with the molecule which constitutes the carrier multiplication layer 62, and ionization is caused. Thus, the drift of the electron which carried out multiplication is countered and carried out to the electric field which go to the carrier multiplication layer 62 from the semi-conductor substrate 61, and it reaches the semi-conductor substrate 61. At this time, avalanche multiplication gain is about 30 and is Photoelectron e. - The total gain of the electron to receive is 105. Extent is reached.
[0055] Here, the carrier multiplication layer 62 of p mold is n+. By being grown epitaxially and formed on the semi-conductor substrate 61 of a mold, dopant distribution of the carrier multiplication layer 62 is controlled very much by homogeneity. Therefore, avalanche multiplication gain is reducing the dependence over the generating location of the secondary electron in an avalanche multiplication field, and has obtained good uniformity.
[0056] The reverse current corresponding to the amount of multiplication of such secondary electron is outputted to an external arithmetic unit through a wire 71 and the terminal rod 72 from the ohmic electrode layer 68. Therefore, based on the drive of an external arithmetic unit, the number of the photon which carried out incidence to the photomultiplier tube 10 is detected according to an individual one by one. therefore, the sensibility which reaches a quantum limitation in a feeble light which cannot be sensed with a naked eye -- a single photoelectron -- it is quantitatively measurable with counting.
[0057] Next, the photomultiplier tube of an example and the photomultiplier tube of the conventional example were made as an experiment, and comparative experiments were conducted.
[0058] The photomultiplier tube made as an experiment based on the example was constituted completely

like the photomultiplier tube of the 1st example of the above. That is, in the semiconductor device, the carrier multiplication layer was formed with epitaxial growth, using Si as a semiconductor material. On the other hand, the photomultiplier tube made as an experiment as a conventional example was the usual photomultiplier tube which has the dynode of a 12-step configuration as an electron multiplier.
[0059] In addition, in the electron multiplier of the conventional example, the 1st step dynode was formed by GaP and the step [2nd] - 12th step dynode was formed by Cu-Be. Therefore, especially the photomultiplier tube of the conventional example had the highest energy resolution which can be attained as a conventional technique by the component of the 1st step dynode.
[0060] By irradiating a near infrared ray to these photomultiplier tubes, energy resolution was measured, respectively. Here, the experiment conditions of the photomultiplier tube made as an experiment according to the example were as follows.
[0061]
Acceleration voltage to a photoelectron : -17kV, bias voltage:145V which were impressed to the semiconductor device, amplifier linked to a semiconductor device : Ortec Model 142A, the light source : LED (RED), ambient temperature : 25 degrees C
Moreover, the experiment conditions of the photomultiplier tube made as an experiment by the conventional example were as follows.
[0062]
Acceleration voltage to a photoelectron : Amplifier linked to -2.000kV and a semiconductor device : Canberra Model 2005, the light source : LED (RED), ambient temperature : 25 degrees C
The output pulse pulse-height distribution of the photomultiplier tube made as an experiment according to the example to drawing 3 are shown. The output pulse pulse-height distribution of the photomultiplier tube made as an experiment by the conventional example to drawing 4 are shown. In these graphs, energy proofreading is given to an axis of abscissa, it is Channel Number corresponding to an incident light child's amount of energy, and an axis of ordinate is Counts which detected the incident light child who has the amount of energy corresponding to each Channel Number.
[0063] consequently, in the conventional photomultiplier tube, it turns out in the photomultiplier tube of this invention that the energy resolution to a single photoelectron is resembling 14% markedly, and it is improving as compared with 30% - 100% of energy resolution to a single photoelectron. Moreover, also in the bottom of the conditions which considered the noise by the amplifier linked to a semiconductor device, the energy resolution to a single photoelectron hardly deteriorates theoretically. Therefore, the energy resolution to an incident light child can be sharply raised by attaining the uniformity of the gain in the carrier multiplication layer of a semiconductor device.
[0064] Here, in the conventional electron tube which contained PD as a semiconductor device, 4.3% of energy resolution to a single photoelectron is obtained under the ideal conditions which removed the noise by the amplifier linked to a semiconductor device. However, the total gain over a photoelectron is 4x103. Extent and since it is comparatively small, under the realistic conditions which considered the noise by amplifier, it will decrease to 40% - 70% of energy resolution to a single photoelectron.
[0065] Moreover, in conventional PMT (PhotomultiplierTube) which built in a multistage dynode and a multistage anode plate, the secondary electron multiplication factor by the dynode of the first rank is comparatively as small as 10. however, the secondary electron multiplication factor according to the breakdown voltage control layer 64 of the first rank with the photomultiplier tube of this invention -- 4x103 it is -- since -- it is large far rather than the secondary electron multiplication factor in conventional PMT. In addition, as compared with this conventional PMT, the improvement in the energy resolution in the photomultiplier tube of this invention originates in the secondary electron multiplication factor by the dynode of the first rank being large.
[0066] As compared with the photomultiplier tube of the 1st example of the above, 2nd example this example changes a part of semiconductor device, and is constituted.
[0067] As shown in drawing 5 , the square pole-like semiconductor device 60 is constituted as APD almost like the 1st example of the above. However, unlike the 1st example of the above, the carrier multiplication layer 62 has about 30 micrometers of thickness, B is doped by concentration abbreviation 1013-1015cm-3 as a p mold dopant, and it has specific resistance about ten to 1000 ohm-cm, and is formed. Moreover, the guard ring layer 63 has about 50 micrometers of the same thickness as the thickness of the carrier multiplication layer 62, and is formed.
[0068] Furthermore, unlike the 1st example of the above, the concave separation slot 69 in a circle has the depth which arrives at the front face of the semi-conductor substrate 61 in the center section of the guard

ring layer 63, and is formed in it. The insulating layer 70 is deposited and formed in the whole front face of this separation slot 69.
[0069] This insulating layer 70 is the insulating thin film formed with the nitride of Si. The thickness of this insulating layer 70 is about 100nm. In case photoelectric cathode 40 is formed, in order not to degrade the semi-conductor property of the carrier multiplication layer 62, an insulating layer 70 is made to deposit on the front face of the carrier multiplication layer 62, and is formed.
[0070] In addition, APD which has such a separation slot is indicated by JP,57-10987,A at the detail, for example.
[0071] Next, the production process of this example is explained.
[0072] As the 2nd step following the 1st step in the production process of the 1st example of the above, a disc-like mask layer is formed on the center section of the insulating layer 66 based on the usual photolithography technique. Next, by using the KOH solution heated as an etching solution based on the usual wet etching method, the periphery of an insulating layer 66 and the guard ring layer 63 is removed, the front face of the semi-conductor substrate 61 is exposed, and the separation slot 69 is formed. Then, based on the usual CVD method, on the whole surface of an insulating layer 66 and the separation slot 69, the nitride of Si is made to deposit and insulating layers 67 and 70 are formed.
[0073] As the 3rd step, a circular ring-like mask layer is formed on the periphery of an insulating layer 67 based on the usual photolithography technique. Then, based on the usual dry etching method, the center section of the insulating layers 66 and 67 is removed, the front face of the breakdown voltage control layer 64 is exposed, and the acceptance section 65 is formed. And based on the usual vacuum deposition method, on the acceptance section 65 and an insulating layer 67, aluminum is made to deposit and the ohmic electrode layer 68 is formed. Then, based on the usual photolithography technique, a circular ring-like mask layer is formed on the surface field of the ohmic electrode layer 68 from the inside section of an insulating layer 67 to the periphery of the breakdown voltage control layer 64. Then, after removing the ohmic electrode layer 68 from on the center section of the breakdown voltage control layer 64 the periphery top of an insulating layer 67 based on the usual wet etching method, a mask layer is removed from on this fabricated ohmic electrode layer 68.
[0074] Next, an operation of this example is explained.
[0075] This example acts almost like the photomultiplier tube of the 1st example of the above. However, in the semiconductor device 60, the thickness and specific resistance of the carrier multiplication layer 62 are greatly set up as compared with the above-mentioned example. Thereby, if a reverse bias electrical potential difference is impressed to the interior of a semiconductor device 60 based on the drive of an external voltage source, the depletion layer prolonged toward the breakdown voltage control layer 64 from the plane of composition of the semi-conductor substrate 61 and the carrier multiplication layer 62 will be formed by comparatively large thickness. Therefore, since the capacity of an avalanche multiplication field becomes small, a working speed improves. therefore, a feeble light which cannot be sensed with a naked eye -- much more -- high sensitivity -- a single photoelectron -- it is quantitatively measurable with counting.
[0076] It is not restricted to many above-mentioned examples, and this invention can perform various deformation here.
[0077] Moreover, the acceptance section of a semiconductor device is exposed and formed in many above-mentioned examples. However, even if the acceptance section of a semiconductor device covers and forms the acceptance section by the insulating layer which consists of a nitride, when electrification by the exposure of a photoelectron is a minute amount, it is suitable.
[0078] Moreover, in many above-mentioned examples, Si is used as the base as a component of a semi-conductor substrate, a carrier multiplication layer, and a breakdown voltage control layer. However, as a component of semi-conductor layers various [these], it is also suitable to use InGaAs.
[0079] Furthermore, it sets in many above-mentioned examples, and is n+, respectively as a conductivity type of a semi-conductor substrate, a carrier multiplication layer, and a breakdown voltage control layer. A mold, p mold, and p+ The mold is set up. However, when germanium is used as the base as a component of semi-conductor layers various [these], it is p+, respectively as a conductivity type of a semi-conductor substrate, a carrier multiplication layer, and a breakdown voltage control layer. A mold, n mold, and n+ Even if it sets up a mold, the almost same operation effectiveness as the above-mentioned example is acquired.
[0080]
[Effect of the Invention] As explained to the detail above, if an external feeble light carries out incidence to the entrance window of an envelope as a photon in the photomultiplier tube of this invention, a

photoelectron will be emitted from photoelectric cathode and incidence will be carried out to the acceptance section of a semiconductor device. The secondary carrier generated by energy disappearance of this photoelectron repeats and carries out multiplication of the process which generates an electronic-electron hole pair. Furthermore, while arrived at the avalanche multiplication field, and a carrier repeats and carries out multiplication of the avalanche multiplication process in which the component of a carrier multiplication layer is made to ionize.

[0081] Here, the dopant distribution is controlled very much by homogeneity by growing epitaxially and forming a carrier multiplication layer on the semi-conductor substrate which has a different conductivity type from this. Therefore, avalanche multiplication gain reduced the dependence over the generation-of-carriers location in an avalanche multiplication field, and has obtained good uniformity.

[0082] Since the reverse current corresponding to the amount of multiplication of such a carrier is outputted from an ohmic electrode layer, the number of the photon which carried out incidence to the photomultiplier tube is detected according to an individual one by one. Therefore, by measurement by the conventional photomultiplier tube, it is extended to measuring an incident light child's number by measurement by the photomultiplier tube of this invention as compared with having been restricted to detecting an incident light child's existence. therefore, the sensibility which reaches a quantum limitation in a feeble light which cannot be sensed with a naked eye according to the photomultiplier tube of this invention -- a single photoelectron -- it is quantitatively measurable with counting.

[Translation done.]

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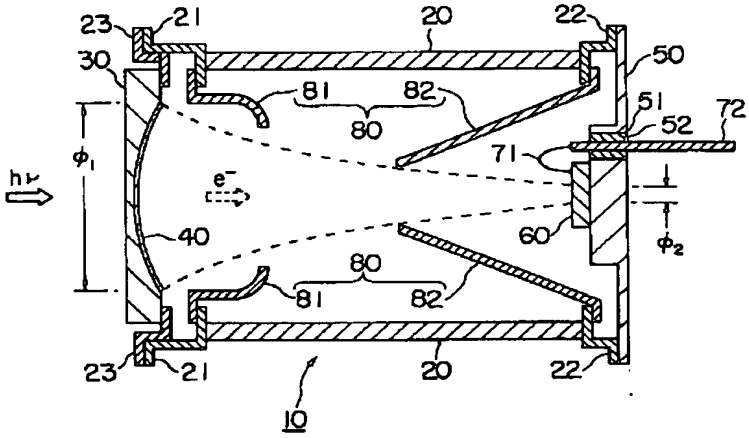
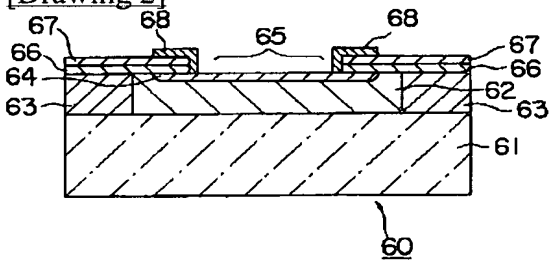
DRAWINGS

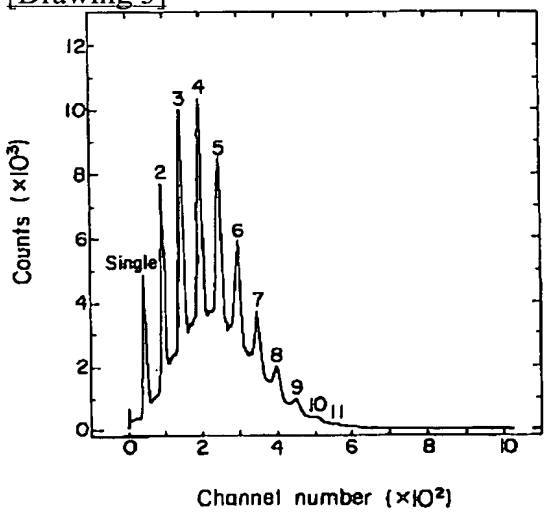
[Drawing 1]



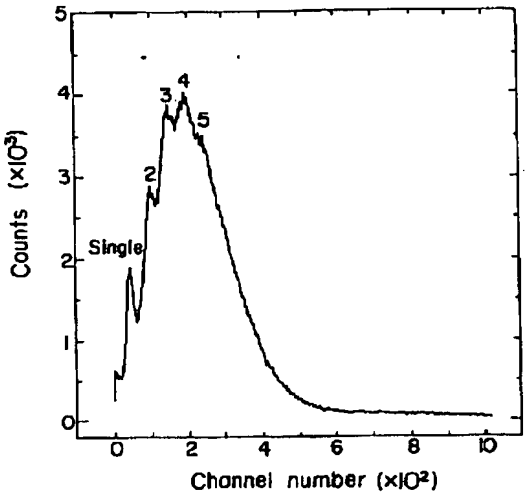
[Drawing 2]



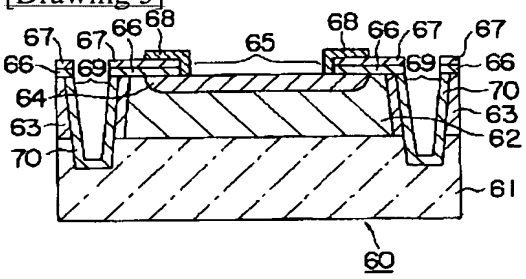
[Drawing 3]



[Drawing 4]



[Drawing 5]



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CORRECTION OR AMENDMENT

[Kind of official gazette] Printing of amendment by the convention of 2 of Article 17 of Patent Law
[Section partition] The 1st partition of the 7th section
[Publication date] January 18, Heisei 14 (2002. 1.18)

[Publication No.] JP,8-148113,A
[Date of Publication] June 7, Heisei 8 (1996. 6.7)
[Annual volume number] Open patent official report 8-1482
[Application number] Japanese Patent Application No. 6-290070
[The 7th edition of International Patent Classification]

H01J 43/12
H01L 31/107

[FI]

H01J 43/12
H01L 31/10 B

[Procedure revision]
[Filing Date] July 30, Heisei 13 (2001. 7.30)
[Procedure amendment 1]
[Document to be Amended] Specification
[Item(s) to be Amended] Claim
[Method of Amendment] Modification
[Proposed Amendment]
[Claim(s)]
[Claim 1] The envelope which holds the interior to a high vacuum,
Photoelectric cathode which emits into a vacuum the photoelectron which it was formed in the vacuum side of the entrance window of this envelope, and was excited by incident light,
The semiconductor device which detects said photoelectron which countered with this photoelectric cathode, was installed in the interior of said envelope, and was emitted from the photoelectric cathode concerned
Preparation,
Said semiconductor device is the semi-conductor substrate of the 1st conductivity type,
The carrier multiplication layer of the 2nd conductivity type formed by growing epitaxially on this semi-conductor substrate,
The breakdown voltage control layer of the 2nd conductivity type which is formed on this carrier multiplication layer and has larger dopant concentration than the dopant concentration of the carrier multiplication layer concerned,
it forms on this breakdown voltage control layer -- having -- a part of breakdown voltage control layer concerned -- a front face -- a wrap ohmic electrode layer,
since -- it constitutes -- having
A part of part which is not covered with said ohmic electrode layer among the front faces of the breakdown voltage control layer concerned is the acceptance section which receives said photoelectron emitted into the vacuum,

The periphery surrounding said acceptance section is covered with the insulating layer which consists of a nitride,
The photomultiplier tube characterized by things.
[Claim 2] It is the photomultiplier tube according to claim 1 which is installed between said photoelectric cathode and said semiconductor devices, is further equipped with the electron lens which converges said photoelectron emitted from the photoelectric cathode concerned, and is led to said acceptance section of the semiconductor device concerned, and is characterized by the aperture of said acceptance section being 10mm or less.
[Procedure amendment 2]
[Document to be Amended] Specification
[Item(s) to be Amended] 0011
[Method of Amendment] Modification
[Proposed Amendment]
[0011] The carrier multiplication layer of the 2nd conductivity type formed by a semiconductor device growing epitaxially here on the semi-conductor substrate of the 1st conductivity type, and this semi-conductor substrate, The breakdown voltage control layer of the 2nd conductivity type which is formed on this carrier multiplication layer and has larger dopant concentration than the dopant concentration of the carrier multiplication layer concerned, it forms on this breakdown voltage control layer -- having -- a part of breakdown voltage control layer concerned -- a front face with a wrap ohmic electrode layer since -- a part of part which is constituted and is not covered with said ohmic electrode layer among the front faces of the breakdown voltage control layer concerned is the acceptance section which receives said photoelectron emitted into the vacuum, and the periphery surrounding said acceptance section is characterized by what is covered with the insulating layer which consists of a nitride.
[Procedure amendment 3]
[Document to be Amended] Specification
[Item(s) to be Amended] 0013
[Method of Amendment] Deletion
[Procedure amendment 4]
[Document to be Amended] Specification
[Item(s) to be Amended] 0019
[Method of Amendment] Modification
[Proposed Amendment]
[0019] The reverse current corresponding to the amount of multiplication of such a carrier is outputted to an external arithmetic unit from an ohmic electrode layer. Therefore, based on the drive of an external arithmetic unit, the number of the photon which carried out incidence to the photomultiplier tube is detected according to an individual one by one. therefore, the sensibility which reaches a quantum limitation in a feeble light which cannot be sensed with a naked eye -- a single photoelectron -- it is quantitatively measurable with counting. Furthermore, since the periphery surrounding the acceptance section of a breakdown voltage control layer is covered with the insulating layer which consists of a nitride, it can avoid degrading the semi-conductor property of the layer covered with the insulating layer.
[Procedure amendment 5]
[Document to be Amended] Specification
[Item(s) to be Amended] 0082
[Method of Amendment] Modification
[Proposed Amendment]
[0082] Since the reverse current corresponding to the amount of multiplication of such a carrier is outputted from an ohmic electrode layer, the number of the photon which carried out incidence to the photomultiplier tube is detected according to an individual one by one. Therefore, by measurement by the conventional photomultiplier tube, it is extended to measuring an incident light child's number by measurement by the photomultiplier tube of this invention as compared with having been restricted to detecting an incident light child's existence. therefore, the sensibility which reaches a quantum limitation in a feeble light which cannot be sensed with a naked eye according to the photomultiplier tube of this invention -- a single photoelectron -- it is quantitatively measurable with counting. Furthermore, since the periphery surrounding the acceptance section of a breakdown voltage control layer is covered with the insulating layer which consists of a nitride, it can avoid degrading the semi-conductor property of the layer covered with the insulating layer.

[Translation done.]